Self-Sustaining Breeding in Advanced Reactors: Comparison of Fuel Cycle Performance

Jiri Krepel, Paul Scherrer Institut, Villigen, Switzerland

Glossary

Ac Actinides, elements with atomic numbers 89 to 103.

AcCl Label for tetra-chloride salt of actinides $AcCl_4$.

Actinides Eigen-composition Stabilized actinides composition, an equilibrium composition which results from a long irradiation of one parent nuclide or their mixture. Necessary condition for the stabilization is that the mass of parent nuclide/s and the irradiation flux do not vary strongly. It is specific and inherent feature for every reactor and every parent nuclide/s and it represents the Eigen-vector of the respective Bateman equation.

B&B Breed-and-Burn; a mode of open cycle operation, where the fissile excess bred during irradiation is equal or higher than the discharged fissile mass after the irradiation. The reactor burns its own bred fuel. The discharged fuel does not need to be recycled and the fresh fuel does not need to contain primordial or synthetic fissile nuclides.

BG Breeding gain, BG = BR-1.

BR Breeding ratio, it is ratio between breeding rate and fission rate. In a self-sustaining breeder BR ? 1.

Breeding Transmutation of actinide nuclide initiated by neutron capture, which increases fission probability. Typically, primordial non-fissile (fertile) nuclides ^{232}Th and ^{238}U are transmuted into synthetic (man-made) fissile ^{233}U and ^{239}Pu.

Burnup Share of already fissioned actinides. It can be expressed in FIMA % (Fissions per Initial Metal Atom) or as energy released from given mass of actinides in MWd/kg (Megawatt days per kilogram). Since the energy per fission is approximately the same for all actinide nuclides, values expressed in these two units are proportional and roughly 10 times higher for the second unit.

Closed cycle A chain of process steps which is closed for the respective working medium. The medium, in nuclear fuel cycle the actinides, is recycled and does not extensively leave the chain.

Cross-section A measure of the probability that neutron will interact when flying by with the respective nucleus (microscopic cross-section) or when fling through with the respective nuclei concentration (macroscopic cross-section).

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Equilibrium reactivity Reactivity provided by actinides Eigen-composition.
FPs Fission products, typically two fragments of actinides fission.
FLI Label for eutectic mixture of lithium fluoride salt and actinides tetra-fluoride salt LiF-AcF_4.
FLIBE Label for eutectic mixture of lithium fluoride and beryllium di-fluoride with addition of actinides tetra-fluoride salt LiF-BeF_2-AcF_4.
Irradiation chain Series of consecutive transmutations and of the respective daughter products induced by neutron irradiation of one parent nuclide, e.g., ^{232}Th or ^{238}U. The radioactive decays of the daughter products are part of the chain.
MA Minor actinides, synthetic actinides originated by uranium transmutation (Np, Am, Cm and higher elements) without Pu, which is some time called major actinide.
NaCl Label for eutectic mixture of sodium chloride salt and actinides tetra-chloride salt NaCl-$AcCl_4$.
Neutron economy Balance between neutron generation and neutron losses in a reactor. Good neutron economy has high neutron generation and small neutron losses by parasitic absorption and leakage from the reactor.
Open cycle A chain of process steps which is open for the respective working medium. The medium, in nuclear fuel cycle the actinides, is not recycled and leaves extensively the chain.
Primordial actinides Actinide nuclides, presumably originated by rapid neutron capture process during a supernova explosion, which have long enough half-life for radioactive decay to be still present on the earth.
Reactivity Reactivity is related to the effective (k_{eff}) or infinite (k_{inf}) neutron multiplication factor. Reactivity denotes the deviation from the self-sustaining fission chain reaction ($k = 1$), for which it is equal to zero. Reactor with negative reactivity ($k < 1$) cannot sustain the fission chain reaction. Positive reactivity ($k > 1$) means that there are more neutrons than needed for the self-sustaining fission chain reaction. From operational perspective, neutron absorber should compensate positive reactivity to control the chain reaction. From fuel cycle perspective, positive reactivity indicate that there are excess neutrons available for additional utilization by breeding or transmutations.
Self-sustaining breeding Breeding process where breeding rate ? fission rate, the mass of fissile synthetic nuclides is conserved in the reactor, and fission chain reaction is sustained solely by these synthetic nuclides. A long time-horizon is being considered in this article.
Subcritical/critical core A core that cannot/can sustain a fission chain-reaction.
Synthetic actinides Actinide nuclides originated, typically by neutron-induced transmutation, from primordial actinides. Synthetic nuclides are, by definition, a much broader group than minor actinides (MA) or trans-uranic elements. For thorium and uranium elements, both primordial and synthetic isotopes exist.
Waste Waste is unwanted side product, which is further unusable. In nuclear fuel cycle, synthetic actinides represent a side product, which is reusable. However, they can be declared as a waste by nuclear fuel cycle policy or when it is laborious to recover them, e.g., from reprocessing losses of certain fuel forms.

Abbreviations

FHR Fluoride High temperature Reactor
GFR Gas cooled Fast Reactor
HPLWR High Performance Light Water Reactor
HTR High Temperature Reactor
LFR Lead cooled Fast Reactor
LWR Light Water Reactor
MCFR Molten Chloride Fast Reactor
MFBR Metal fueled Fast Breeder Reactor
MSFR Molten Salt Fast Reactor
MSR Molten Salt Reactor (graphite moderated)
PHWR Pressurized Heavy Water Reactor
RBMK Reaktor Balshoi Moshnosti Kanalnyj (high-power graphite moderated water cooled channel-type reactor)
SFR Sodium cooled Fast Reactor

Introduction

This is the third of a series of three chapters that is dedicated to the identification of the advanced reactor technologies that are capable of self-sustaining breeding when fueled with either ^{232}Th or ^{238}U, and to the investigation of equilibrium fuel cycles

properties and neutronics performance. The first chapter (Krepel, 2021) characterizes the available fuel resources from the nuclear and reactor physics perspective. The second chapter (Krepel and Losa, 2021) determines the equilibrium fuel composition in advanced reactors and compares the basic features of the equilibrium fuel cycle and selected reactor neutronic performance characteristics at the equilibrium state. This third chapter evaluates the fuel cycle performance from a neutronics perspective by means of the earlier obtained equilibrium parameters. It provides an additional insight on why some advanced reactor concepts can act as self-sustaining breeders in a closed or even an open cycle, while others do not.

Nuclear fuel cycle

The purpose of the nuclear fuel cycle, and of nuclear reactors as such, is energy production in two major forms: electricity and heat. The nuclear fuel cycle can be perceived from different perspectives. From a cosmological perspective, the nuclear fuel cycle consists of: first generation star formation following the big-bang (Garcia, 2021), supernova explosions of such first generation stars, ensuing second generation stars and planets formation, and finally primordial actinides utilization on planet Earth by mankind. Hence, the nuclear fuel resources are not renewable, and our aim should be to maximize their utilization with minimal waste production. From the more classical perspective, the nuclear fuel cycle includes stages before the irradiation: exploration, mining, milling, conversion, enrichment and fabrication (Crawford, 2021), the irradiation stage itself, and stages after the irradiation: interim storage, transportation, reprocessing, transmutation and waste disposal (Glatz, 2021). This article focuses solely on the irradiation phase. However, it has implications also for the other phases. For instance, the product of exploration, mining, milling and conversion is natural uranium. Based on the current irradiation scheme, we utilize less than 1% of the mined material, while 80% is stored in form of depleted uranium as the residuum from enrichment process, and 19% is discharged with the irradiated fuel. Higher utilization of the natural uranium resource will reduce the environmental impact, per unit of produced energy, of both uranium mining and enrichment.

Fuel cycle performance parameters

From the irradiation perspective, the major fuel cycle performance parameters are:

- breeding capability,
- achievable burnup,
- initial fissile mass,
- means of criticality maintenance, and
- transmutation capability.

The neutron economy is not listed as a standalone performance parameter. Nonetheless, since it effects all other parameters, it is analyzed in depth. Natural resources utilization is also not listed as a performance parameter. There is a big difference between the ^{235}U-fueled open cycle, where the natural uranium utilization does not exceed 1%, and the self-sustaining breeding in closed cycle (Wigeland, 2021), where the utilization of thorium and natural uranium can reach up to 95–98%. However, within these two fuel cycles types, the differences in terms of natural resources utilization are minimal. Accordingly, the breeding capability suffices as indicator for resources utilization, and the Breeding Ratio (BR) is used here as its measure.

However, there is one type of open cycle, where the utilization can be substantially larger than 1%. In so called breed-and-burn (B&B) open cycle mode, the natural uranium utilization can reach up to 20–35% (Qvist, 2021; Krepel and Kramer, 2021; Greenspan, 2021). For this type of self-sustaining breeding in open cycle only the basic criteria for B&B operation are evaluated and discussed. Similarly, there are also safety related fuel cycle parameters. While these are not part of this study, the temperature coefficients of reactivity are addressed in Krepel and Losa (2021).

Compared reactor concepts

In this article the fuel cycle performance of 16 selected reactors is assessed. For details of their selection and their basic description, please refer to chapter (Krepel and Losa, 2021). The major criterion for the selection was to cover the majority of the advanced reactor concepts (Stanculescu, 2021) and the highest possible variety of the core neutron spectra. For readers' convenience the reactor labels are listed here in the same order used in the charts and tables:

FHR	Fluoride High temperature Reactor
HTR	High Temperature Reactor
RBMK	Reaktor Balshoi Moshnosti Kanalnyj (high-power graphite moderated water cooled channel-type reactor)
PHWR	Pressurized Heavy Water Reactor
MSR-FLIBE	Graphite moderated Molten Salt Reactor with fuel in form of eutectic mixture of lithium fluoride and beryllium di-fluoride with addition of actinides tetra-fluoride salts
MSR-FLI	Graphite moderated Molten Salt Reactor with fuel in form of eutectic mixture of lithium fluoride and actinides tetra-fluoride salts
HPLWR	High Performance Light Water Reactor

(Continued)

LWR	Light Water Reactor
MSFR-FLIBE	Molten Salt Fast Reactor with fuel in form of eutectic mixture lithium fluoride and beryllium di-fluoride with addition of actinides tetra-fluoride salts
MSFR-FLI	Molten Salt Fast Reactor with fuel in form of eutectic mixture of lithium fluoride and actinides tetra-fluoride salts
LFR	Lead cooled Fast Reactor
SFR	Sodium cooled Fast Reactor
GFR	Gas cooled Fast Reactor
MFBR	Metal fueled Fast Breeder Reactor
MCFR-NaCl	Molten Chlorides Fast Reactor with fuel in form of eutectic mixture of sodium chloride and actinides tetra-chloride salts
MCFR-AcCl	Molten Chlorides Fast Reactor with fuel in form of actinides tetra-chloride salts

The order of the reactors in the presented charts and tables was selected based on spectral index (Losa, 2016). For more discussion about equilibrium spectrum but also about assumptions and simulation tools refer to Krepel and Losa (2019, 2021).

Methods of fuel cycle performance assessment

Direct irradiation simulation

The basic method of fuel cycle performance evaluation is the direct irradiation simulation of an open cycle and comparison of the BR, achieved burnup, and differences between initial and irradiated fuel compositions. The major disadvantage of this method is that the initial fuel composition itself determines the BR and the respective reactor type (see **Fig. 2**). Furthermore, different initial compositions result in different achievable burnups. It is therefore hard to make general conclusions about the fuel cycle performance and inter-compare reactor types by means of the open cycle irradiation. It does not necessarily show where the fuel composition tends to converge, and whether the reactor would be critical at equilibrium. The BR obtained by direct irradiation simulation is often not sustainable, because not all daughter products concentrations are fully equalized. Unlike in the open cycle, explicit simulation of repetitive irradiation in a closed cycle is one of the most accurate methods to evaluate the ultimate fuel cycle performance (Krepel et al., 2012). Nonetheless, depending on the applied code, it is usually also the most time demanding simulation.

D-factors

Two more general methods have been proposed in OECD (2006) to evaluate actinides impact on the fuel cycle performance. Even though they were predominantly designed for synthetic actinides transmutation, they are also valid for the breeding. Both these methods rely in one or another way on the stabilized irradiation chain. The first method is based on so called D-factors. These factors represent the number of neutrons which are needed to ultimately fission one atom of a given nuclide. Accordingly, the knowledge of the respective irradiation chain is needed, because the D-factors account also for the neutron consumption by daughter products (Salvatores et al., 1994). The D-factors provide direct information about the neutron cost for the ultimate transmutation of given nuclide. Depending on the spectrum and nuclide type, D-factors can be positive (neutron consumption) or negative (neutron production). The D-factors thus quantify additional burden or gain for the neutron economy in a reactor loaded by external synthetic actinides. Since breeding is nothing else than a ^{232}Th or ^{238}U transmutation, the D-factors of ^{232}Th and ^{238}U actually indicate the neutron balance of a breeder. Since negative D-factor means that neutrons are produced, the ^{232}Th or ^{238}U D-factors should be negative to enable breeding (Krepel and Losa, 2016).

There are four basic Reactions (R) ongoing in nuclear reactor, where each of them can result in neutron production or consumption C^R:

1. (n, 2n), producing one neutron ($C^1 = -1$)
2. neutron capture (n, γ), consuming one neutron ($C^2 = 1$)
3. radioactive decay, no interaction with neutron ($C^3 = 0$)
4. fission (n, f), consuming one and producing ν neutrons ($C^4 = 1 - \nu$)

The other interactions with neutrons were neglected in this evaluation. The D-factor for certain nuclide I is calculated from the knowledge of the irradiation chain and rely on the reaction probability P of the reaction type R which is multiplied by the above listed neutron consumptions C. These products should be summed up for all reactions, accounting also for the daughter products:

$$D_I = \sum_{R1=1}^{4} P_{I\to I_{R1}} C_I^{R1} + \sum_{R1=1}^{4} P_{I\to I_{R1}} \left(\sum_{R2=1}^{4} P_{I_{R1}\to I_{R1,R2}} C_{I_{R1}}^{R2} \right) + \sum_{R1=1}^{4} P_{I\to I_{R1}} \left(\sum_{R2=1}^{4} P_{I_{R1}\to I_{R1,R2}} \left(\sum_{R3=1}^{4} P_{I_{R1,R2}\to I_{R1,R2,R3}} C_{I_{R1,R2}}^{R3} \right) \right) + \ldots \quad (1)$$

where, for instance, $I \to I_{R1}$ represent reactions R on a nuclide I of a type 1, 2, 3, or 4 as listed above, which leads to a daughter product I_{R1}. The fission reaction $R = 4$ terminates the transmutation chain. Reactions of the original nuclide I are presented by the first term in Eq. (1), the second term stands for the reactions of its daughters I_{R1}, and the third term for reaction of the daughters of daughters $I_{R1,R2}$ (see **Fig. 1**). Since one of the later daughter products $I_{R1,R2}$, $I_{R1,R2,R3}$, $I_{R1,R2,R3,R4}$, etc. may be identical with the

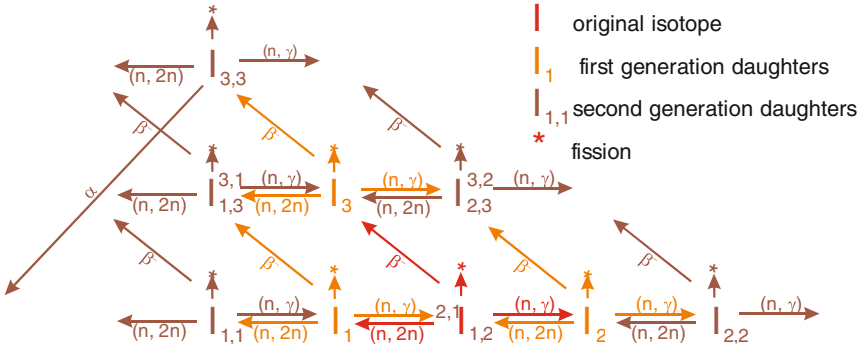

Fig. 1 Example of the D-factor algorithm application. Losa E (2016). *U-Pu and Th-U Fuel Cycle Closure*, PhD thesis. Prague: Czech Technical University in Prague, Department of Nuclear Reactors; Krepel J and Losa E (2016) Enumeration of static and dynamics neutron consumption D-factor for several selected reactors at equilibrium closed fuel cycle, *Proceedings of ICAPP 2016, San Francisco, USA*.

original nuclide I the equation represents an infinite series. For instance, the (n, 2n) and (n, γ) reactions (see Fig. 1) cause that the nuclides I, $I_{2,1}$, and $I_{1,2}$ are identical. Fig. 1 also illustrate the plenitude of possible transmutation paths and the difficulty to compute the D-factors. Nonetheless, since all reactions are properly accounted for, the D-factors of ^{232}Th and ^{238}U accurately describe the neutron balance of a breeder.

Equilibrium method

The second method, proposed in OECD (2006) is actually the equilibrium method. It relies on the fact that if all fuel cycle parameters are fixed, recycling in closed cycle results in the equilibrium fuel composition. One of the fixed parameters is the composition of the fuel feed (make-up fuel). In OECD (2006) the primary aim was synthetic actinides transmutation, and thus the feed included them. This article focuses rather on the resources utilization, and the primordial actinide nuclides ^{232}Th or ^{238}U are exclusively used as the fuel feed. In this case a single irradiation chain represents the whole equilibrium fuel composition, and it is, therefore, the Eigen-vector of the respective Bateman equation (Bateman, 1910). For more detail about equilibrium fuel cycle simulation refer to Krepel and Losa (2021). This reference was also used to adopt the equilibrium fuel composition (stabilized actinides vector or actinides Eigen-composition) and the equilibrium multiplication factors.

One distinguished feature of the equilibrium fuel composition is that the concentrations of all actinides are constant. Per definition, the breeding and fission rates must be in balance for this composition. The rate of ^{232}Th or ^{238}U transmutation is thus equal to the fission rate of synthetic actinides. Hence, for each reactor there exists an equilibrium fuel composition for which BR = 1. However, not all reactors are critical with this fuel composition. Since there is a straightforward relation between BR and reactivity (Krepel et al., 2018), the equilibrium reactivity is used in this study to evaluate the breeding capability.

Breeding capability

Reactor classification

Breeding capability, a foremost fuel cycle performance parameter, defines whether a reactor can or cannot be operated as a self-sustaining breeder in closed cycle, which relies solely on fertile ^{232}Th or ^{238}U feed. It is determined by the neutron economy of the equilibrium state, particularly by the parasitic neutron capture of the equilibrium actinides composition. The breeding capability can be quantified as the ratio between breeding and fission reactions. This ratio is called Breeding Rate (BR), or alternatively also conversion ratio. In some cases the breeding capability is expressed as Breeding Gain (BG), where BG = BR-1. In a self-sustaining breeder, where BR ≥ 1, the fissile mass remains constant or slightly grows (A ≤ B in Fig. 2). In a reactor, where fission (BR < 1) or breeding (BR > 1) dominates, the fissile mass decreases or increases, respectively. However, only the equilibrium BR is relevant for the breeding capability assessment. BR of non-equilibrium fuel compositions does not need to be sustainable. Especially in the Th-U cycle, initial fissile load often consists of ^{233}U, ^{239}Pu, or highly enriched uranium, and BR > 1 can be obtained during the first irradiation cycle. Nonetheless, it does not mean that it is sustainable. Typically, in thermal spectrum systems, BR > 1 during the first irradiation cycle underestimates the parasitic neutron capture of synthetic actinides, e.g., ^{234}U, ^{236}U or ^{237}Np, which obviously did not yet converge to their equilibrium concentrations.

Equilibrium BR can be used to classify reactors into four categories: burner, converter, breeder and B&B (see Fig. 2). In a breeder it is at least equal to 1, in a converter it is below 1, and in a burner it should be at best 0. This would mean that there is no breeding process at all, what is nearly impossible. The BR border between burner and converter is not well defined and ranges from 0.5 to 0.9. Nevertheless, the major difference is that the fertile isotopes ^{232}Th and ^{238}U are usually avoided in burners dedicated to Minor Actinides (MA) transmutation. The minimal BR for a B&B reactor is around 1.5 (see Fig. 6), and thorium fueled reactors practically cannot be operated in B&B mode.

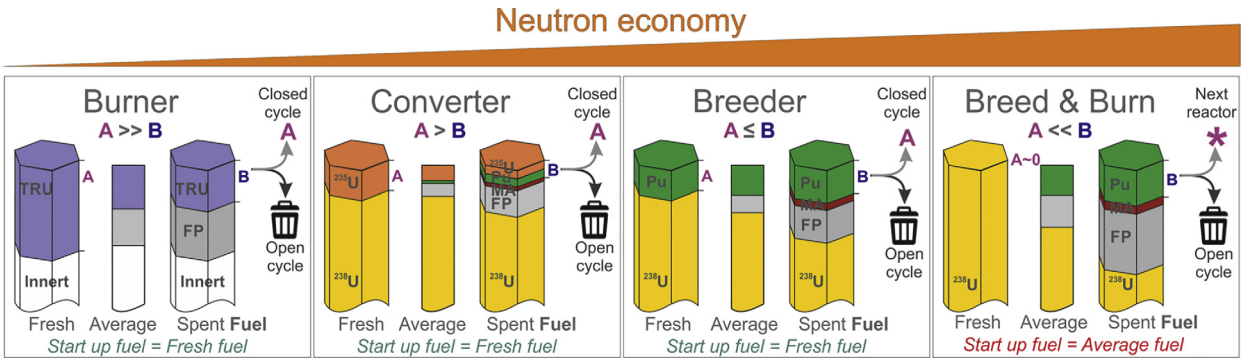

Fig. 2 Illustration of reactor classification by breeding ratio for ^{238}U as a fertile isotope. A is the initial and B the discharged fissile actinides share.

Breeding ratio

The equilibrium multiplication factor k obtained in Krepel and Losa (2021) is smaller than one for some reactors. Using the simple relation from Krepel et al. (2018), BR or BG can be calculated from k and the average number of neutrons per fission $\bar{\nu}$ as follows:

$$BR \cong 1 + \bar{\nu}\frac{k-1}{k} \quad \text{or} \quad BG \cong \bar{\nu}\frac{k-1}{k} \tag{2}$$

The approximate relation in Eq. (2) was derived for the equilibrium state and its accuracy decreases with increasing distance of k from 1. For convenience the breeding capability will be discussed using BG. From the 16 selected concepts, there are only few thermal Th-U cycle reactors with positive or close to zero BG (see Fig. 3). Nonetheless, it should be recalled that the equilibrium multiplication factors, applied for this BG estimate, correspond to an infinite reactor without Fission Products (FPs). The infinite BG presented in Fig. 3, thus, represents hypothetical maximum and not realistic values. The neutron losses by leakage from finite core can be reduced by blanket and/or reflector addition. However, the parasitic neutron absorption by FPs cannot practically be suppressed, since it would result in prohibitively high fuel reprocessing frequencies in thermal breeders. The achievable burnup as the second fuel cycle parameter would be discussed in the next sub-chapter. However, MSR concepts with liquid fuel could potentially be considered as a reasonable thermal spectrum breeders. Since their fuel is liquid, continuous FPs removal strategies might offset high reprocessing frequency penalties. Furthermore, this would allow for removal of higher actinides and questionable separation of ^{233}Pa and its decay outside of the neutron flux to improve the neutron balance (see 3rd and 4th term of Eq. 4).

All fast reactors have positive BG. Only the MSFR-FLIBE with the softest fast spectra, see Fig. 4 from Krepel and Losa (2021), has close to zero but negative BG in the U-Pu cycle. For all other fast reactors BG is almost twice higher in the U-Pu cycle. BG as well as equilibrium multiplication factor are integral parameters and encompass also the impact of non-fuel materials in the core. Even though, non-fuel materials introduce a certain perturbation, it is clear that the U-Pu cycle profits more from the spectrum hardening as compared to the Th-U fuel cycle. Once the ^{239}Pu capture probability decreases in a hard spectrum, the higher average number of neutrons per fission starts to dominate. The Th-U fuel cycle is also performing better in a harder neutron spectrum. However, the

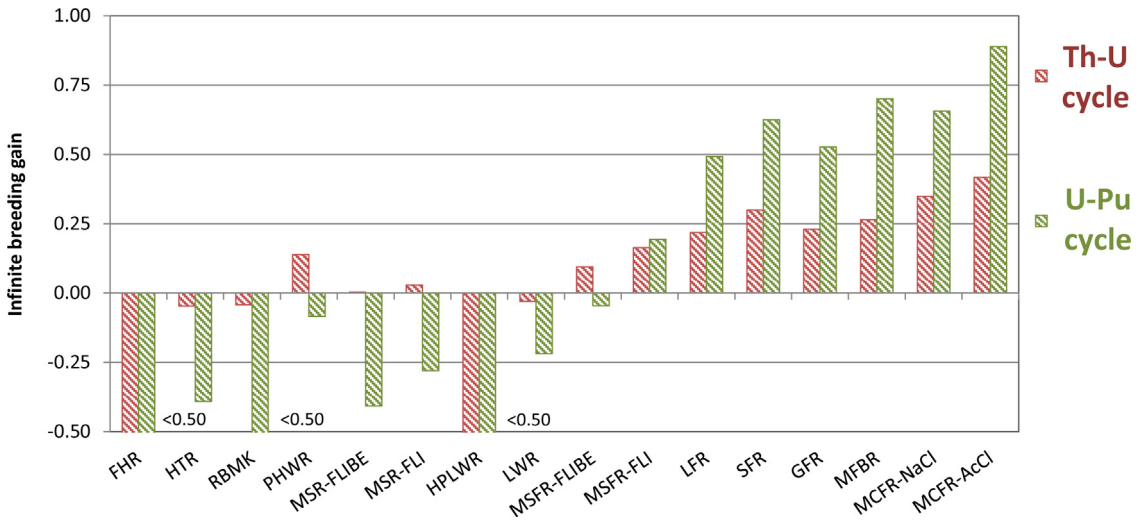

Fig. 3 Infinite breeding gain for Th-U and U-Pu cycles and 16 selected reactors.

trend is much milder, because the ^{233}U capture probability is generally low and less dependent on neutron spectrum. The BG in the Th-U fuel cycle is lower in fast reactors because of the ^{233}U lower average number of neutrons per fission.

Achievable burnup

Once the reactors are classified according to their breeding capability, the second most important performance parameter for the fuel cycle is the achievable burnup. In both open and closed cycles, higher burnup reduces the core reloading frequency and the need of fuel fabrication, transportation and optional reprocessing. Hence, it reduces the fuel cycle costs. Since the amount of synthetic actinides tends to stabilize during the irradiation, higher burnup in an open cycle results in lower waste amount per unit of produced energy. In a closed cycle, it decreases the reprocessing frequency and thus also reduces the waste amount, see Fig. 2 in Krepel (2021). From neutron economy perspective, the achievable burnup is determined by BR, initial fissile mass, and equilibrium fissile mass.

Fission products cumulation

The major issue of burnup is that the neutron economy, but also other fuel mechanical and chemical features, deteriorate during irradiation. In every reactor, FPs accrue during irradiation and increase the parasitic neutron capture. Ultimately, every reactor will become sub-critical if FPs would not be regularly removed. FPs impact on neutron economy depends on their concentration and neutron capture cross-section. Its relative strength is associated with the fissile actinides concentration and fission cross-section. Hence, the deterioration caused by FPs can be pronounced or suppressed by evolution of fissile actinides share and depends also on the absolute value of this share. For equilibrium fuel composition BR = 1, and the share of fissile actinides is constant. Should the initial fissile share be above or below the equilibrium one, the irradiation will result in its decrease or increase, respectively. This has strong implication for actinides parasitic capture itself, but also for the relative FPs strength. Majority of ^{235}U-fueled reactors use thermal spectrum and low enriched uranium. Hence, BR is around 0.2–0.5 and the fissile actinides share is strongly decreasing during the irradiation. Consequently, the relative importance of FPs concentrations and capture cross-sections is growing faster than the respective absolute values.

Impact of absolute fissile share

The absolute share of fissile actinides also indicates how sensitive the neutron economy will be to FPs buildup. The fissile share in the ^{232}Th irradiation chain is roughly 1.5% in thermal and 10% in fast reactors (see **Fig. 4**). A burnup (BU) of 5% FIMA implies that 5% of the actinides are fissioned. At the same time, the FPs mass corresponds to 300% of the fissile actinides mass in thermal and only to 50% in fast reactors. In the U-Pu cycle it is even more pronounced, burnup of 5% FIMA means that the FPs mass can be up to 14 times higher than the fissile mass (see **Fig. 5**). The higher fissile share is actually the major reason why fast reactors are less sensitive to FPs build up. However, it partly depends also on the ratio between FPs capture cross-section and actinides fission cross-sections, which is spectrum dependent. Even though, it is rather a hypothetical example, 1.5% of fissile share in discharged fuel and burnup of 5% FIMA represent reasonable values for typical LWR.

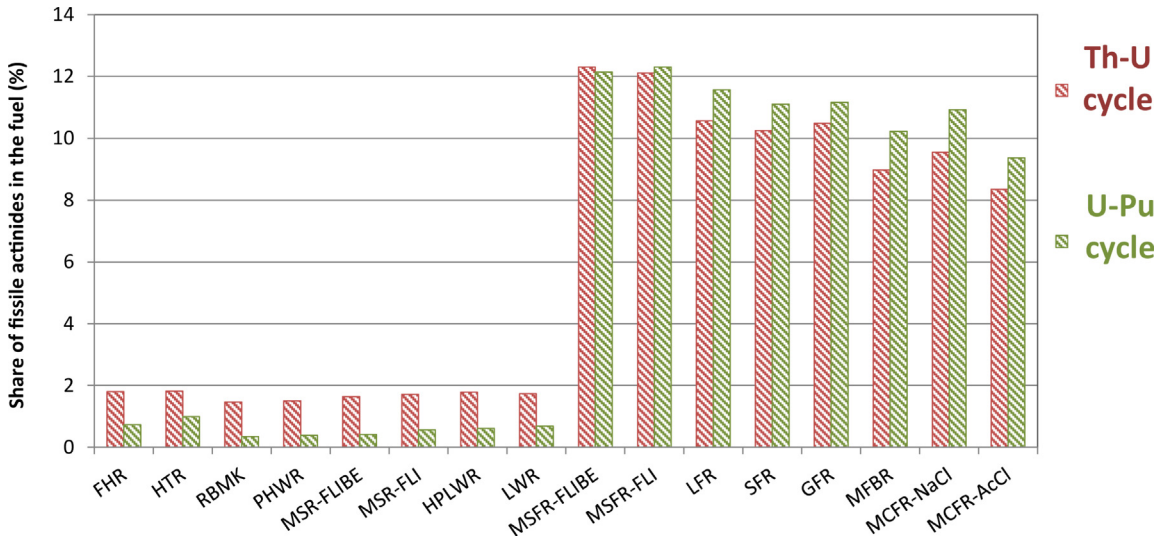

Fig. 4 Share of fissile actinides in the fuel for Th-U and U-Pu cycles and 16 selected reactors.

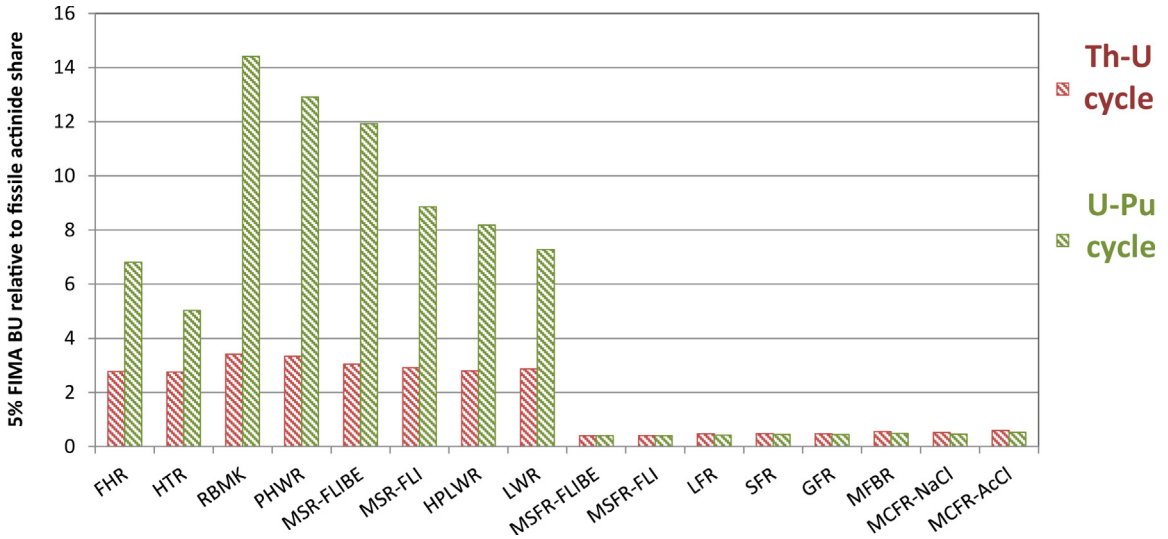

Fig. 5 Ratio between 5% FIMA burnup and fissile actinides share in the fuel for Th-U and U-Pu cycles and 16 selected reactors.

This study does not evaluate achievable burnup as such and it even neglects FPs. Nonetheless, for each reactor, the BR is being assessed and fissile actinides share is provided. In general, the foreseen burnup for fast breeder reactors is usually similar to their fissile actinide share in the core, i.e., around 10% FIMA. Nonetheless, 15–20% is achievable from a neutron economy perspective. Breeding in thermal reactors would likely not even allow for reaching burnup equal to the fissile fuel share.

It should not be forgotten, however, that a reactor core usually consists of several groups of fuel assemblies with different burn-ups to minimize the reactivity oscillations (see Fig. 8). The average FPs share in every core is thus roughly the half of final discharged burnup. Accordingly, for discharged burnup of 20% the average FPs share in the reactors would be 10%. Hence, it would be equal in this example to the fissile actinides share in fast reactors. The exceptions from this rule, are the reactors with liquid fuel (MSR, MSFR, and MCFR) where the fuel is homogeneously mixed, the effective FPs share in the core is averaged, and the final discharged burnup is equal to the average burnup. The achievable burnup in these reactors can be lower. At the same time, the liquid fuel allows for continuous FPs removal. Hence, it partly compensates the averaging effect.

Basic assessment of the B&B cycle

The neutron economy of a breeder is very tight, and the bred synthetic actinides must be recycled to maintain the fissile material balance. The only exception from this requirement are very strong breeders, where the fissile excess bred during the irradiation would be equal or higher than the discharged fissile mass after the irradiation. Since the bred excess is not necessary for the fissile mass conservation, these very strong breeders can self-sustain the breeding in open cycle in the B&B mode (Qvist, 2021). The name is derived from the fact that the loaded fuel does not need to contain fissile actinides; they are bred during the irradiation in the B&B reactor and suitable fraction of them fission in that reactor. The trivial condition for B&B reactor operation is based on the balance of bred synthetic actinides (Krepel et al., 2018). The amount of extra bred fissile synthetic actinides, in a period between two refuelings, should be equal or higher than the amount of fissile synthetic actinides (F_F) removed during the actual refueling:

$$F_F \leq BU \cdot BG \tag{3}$$

where BU is the burnup in absolute FIMA share and the product of BU and BG represent the extra bred amount of fissile synthetic actinides. The presence of burnup in Eq. (3) is also the reason why the B&B cycle assessment is placed after the achievable burnup subsection. This trivial condition for B&B reactor operation can be graphically presented for three particular fissile actinides contents in the core. These are 1%, 2% and 10% and correspond roughly to the equilibrium fissile actinides share in Fig. 4. In thermal reactors, with 1% or 2% of fissile actinides share in the respective U-Pu or Th-U cycle, the overall neutron economy does not allow for B&B operation. The required combination of BG and burnup is not achievable in thermal spectrum. The B&B cycle is possible only in fast reactors. Even though, the fissile actinides share of 10% shifts the respective curve in Fig. 6 higher, the required combination BG and burnup is still more realistic. Assuming burnup of 20% FIMA, BG of 0.5 would be needed for reactor with 10% share of fissile actinides. There are only four concepts with sufficiently high BG in Fig. 3, these are the two sodium cooled concepts and the two MCFR concepts. Since the MCFR concept with liquid fuel allows for partial FPs removal from the core, it can theoretically allow for higher burnup in the B&B open cycle mode (Krepel and Kramer, 2021).

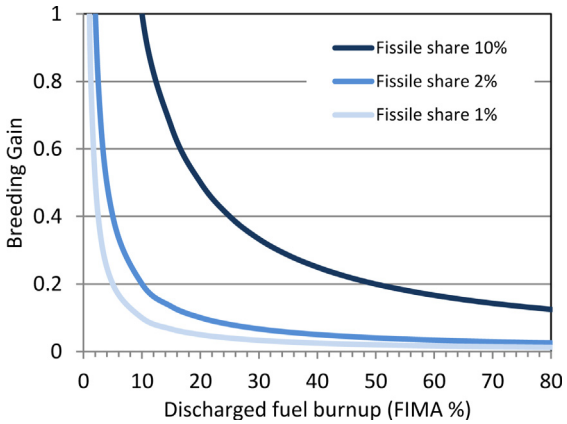

Fig. 6 Relationship between breeding gain, discharged fuel burnup, and fissile share in discharged fuel to enable B&B reactor operation.

Initial fissile mass

As mentioned, nuclear reactors can be divided according to BR into four categories presented in Fig. 2. The breeder and the B&B reactor will, once started, maintain their own fissile mass constant and use only ^{232}Th and ^{238}U (in form of depleted or natural uranium) as the fertile feed. Since the self-sustaining breeder maintains its own fissile share, no matter if in a closed cycle with recycling or in an open B&B cycle, the initial fissile mass does not strongly differ from the equilibrium fissile mass.

The burner reactor is fueled with synthetic actinides, and its objective is maximum reduction of their amount. It should be at best operated in closed cycle. Hence, synthetic actinides represent its initial fuel in open cycle, as well as the feed in closed cycle.

Only converters are extensively operated in an open cycle. Their initial fuel is typically enriched uranium, and their purpose is energy production. The vast majority of ^{235}U-fueled converters has thermal neutron spectrum and cannot be operated as a breeder. The equilibrium share of fissile actinides in thermal reactors is low. In the ^{238}U chain, it is below 1% (see Fig. 4). Hence, it is quite similar to the ^{235}U share in natural uranium. Even though there are exceptions, neither natural uranium nor the ^{238}U irradiation chain can make thermal reactors critical. To be able to operate these reactors, but also to reach a reasonable burnup, the capture rate of ^{238}U needs to be suppressed by uranium enrichment. Since the equilibrium fissile share in ^{238}U chain is below 1%, the 5% ^{235}U enrichment will result in a more than five times lower ^{238}U capture rate. Accordingly, the BR in this simplified example will be roughly 0.2 for 5% enriched uranium.

The initial fissile mass, as well as the transition scenarios towards the equilibrium cycle, are not an objective of this study. For all reactors operated in a closed cycle, the initial fissile mass is determined by the equilibrium fissile share. To provide some insight, the specific density of the main fissile nuclide in the equilibrium state is shown in Fig. 7. It is only an indication of the initial fissile mass requirement. To assess the total masses, it should be multiplied by the approximate core volume (Krepel and Losa, 2021). Furthermore, for a converter operated in an open cycle, the initial fissile mass is correlated with the achievable burnup.

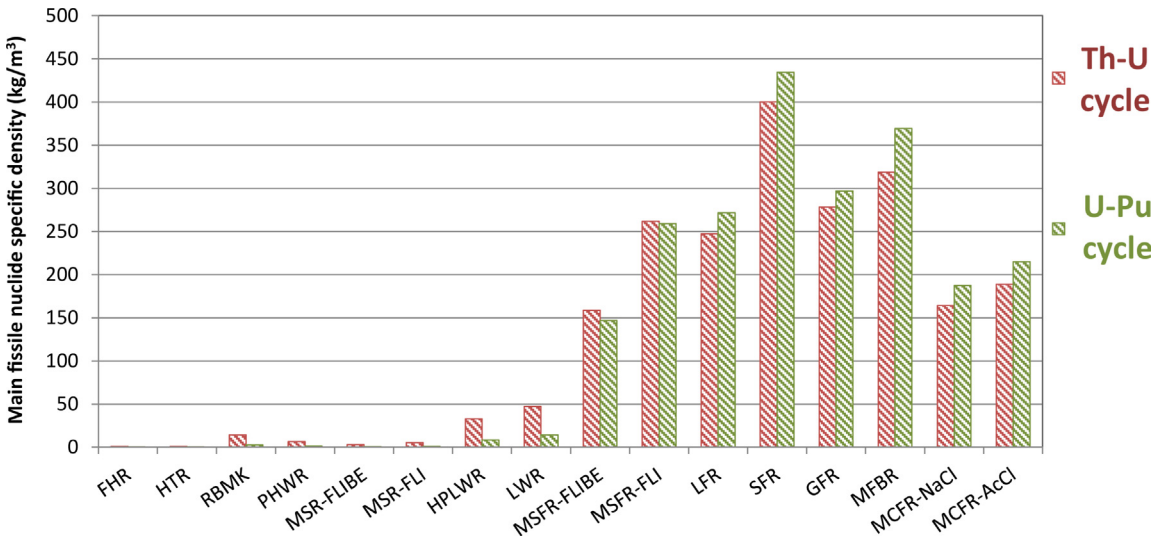

Fig. 7 Main fissile nuclide, i.e., ^{233}U or ^{239}Pu, specific density for Th-U and U-Pu cycles and 16 selected reactors.

Means of criticality maintenance

Means of criticality maintenance are relevant predominantly for the open cycle. In the ^{235}U-fueled reactors, the fission rate strongly dominates over the breeding, and the fissile mass is decreasing during the irradiation. As a consequence, the FPs impact on neutron economy is growing in both absolute and relative terms. To achieve reasonable burnup, the initial ^{238}U capture rate must be suppressed by uranium enrichment. This suppression exceeds the initial criticality needs and causes a huge reactivity excess. This excess needs to be compensated by neutron absorbers, which are either burnable or removable, e.g., control rods. They compensate the initial reactivity excess needed for high burnup and are gradually burned or removed. They are called burnable, because their capture cross-section is very high and their mass low. Hence, their capture rate is strongly decreasing with their transmutation. The primordial nuclides ^{232}Th and ^{238}U can be theoretically also considered as burnable absorbers. However, their capture cross-sections are rather small and absolute mass rather high. Accordingly, the capture rate change is too slow. Nonetheless, ^{232}Th performs slightly better from this perspective and in some reactors it may indeed act as burnable absorber, which is balancing the increasing mass of FPs (Krepel et al., 2015).

In fast reactors operated in a closed cycle or in an open B&B cycle, the fissile fuel share is roughly constant and usually around 10% (see Fig. 4). Nonetheless, the FPs buildup and the ^{232}Th or ^{238}U refilling induces need for regular fuel reloading. The FPs buildup and the actinides composition changes result in reactivity variation during irradiation. Hence, control rods are needed for their compensation. To illustrate these variations the results of a GFR sensitivity study Krepel et al. (2010) are presented in Fig. 8. In this simulation, the GFR was operated as a self-sustaining breeder in closed U-Pu cycle, and different stages of the fuel cycle (irradiation, cooling time before reprocessing, and reprocessing) were explicitly simulated. In the sensitivity study, the cooling time before reprocessing was altered. The objective of the study was to evaluate the impact of ^{241}Pu decay during the cooling period. Since the fissile nuclide ^{214}Pu decays into the fertile nuclide ^{241}Am, the cooling time was actually altering the ratio between fissile and fertile nuclides. Accordingly, the longer cooling time resulted in higher BG at the beginning of irradiation. Fig. 8 is thus prototypical for reactivity variations in a fast breeder reactor as a function of the initial BG.

The left hand side of Fig. 8 shows the reactivity variation caused by FPs buildup and actinide composition change during the irradiation using an one-batch approximation. In this case all assemblies are loaded, irradiated and unloaded together. On the right hand side of Fig. 8, the assemblies are divided into three groups and only one third is removed at a time. In both cases, the reactivity variations are minimal, when the initial BG is positive, and the reactivity firstly grows. This fact is underlined on the right hand side of Fig. 8, where the three-batch operation practically averages the curves from the left hand side. For the cases with highest initial BG, or actually longest cooling time, where the reactivity initially grows (left hand side of Fig. 8), the variation is minimal (bottom curves in right Fig. 8).

The reactivity variations presented above can be avoided in reactors where the FPs are being continuously removed and actinides continuously added to the core. This is the case for MSR, MSFR, MCFR with liquid fuel and for PHWR and HTR (FHR) with small fuel assemblies and online refueling strategy (during power operation). While criticality maintenance is not an objective of this study, it is worthwhile noting that self-sustaining breeders are expected to have much smaller reactivity variation during irradiation than an open cycle operated ^{235}U-fueled reactors. At best, the reactors should have small breeding ratio excess, so that the fissile mass is slightly increased at the beginning of the cycle and balances the subsequent decrease caused by FPs parasitic neutron capture.

Transmutation capability

Some of the advanced reactor concepts are dedicated to the minimization of legacy synthetic actinides. Their performance is thus measured by the transmutation capability. This is an ambivalent term, because even the breeding is a transmutation. Nonetheless, the transmutation refers here rather to the fission, which is the major option to reduce the long-term stewardship burden related to

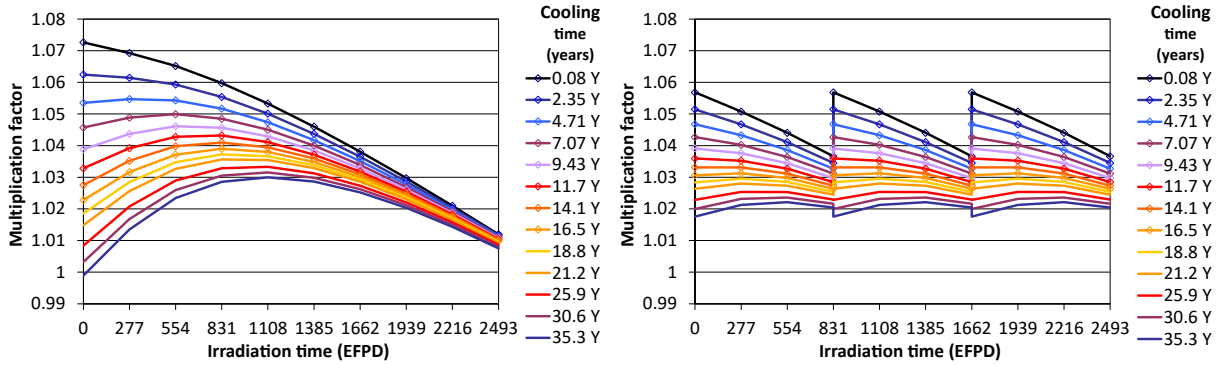

Fig. 8 Neutron multiplication factor evolution during the irradiation in GFR in one-batch approximation (left) and three-batch simulation (right) as a function of fuel cooling time before reprocessing, which changes the initial BG.

synthetic actinides. Furthermore, some concepts are meant to combine both fuel breeding and legacy synthetic actinides transmutation objectives. The usual measure of the transmutation capability is the concentration reduction of selected actinides and the related neutron costs. The reduction can be expressed as the partial fission share of the legacy actinides. The neutron costs are evaluated here by the D-factors.

The fissioned share of legacy actinides in open cycle can be deduced from the difference between the loaded and discharged fuel. Necessary condition for successful transmutation is that the concentration of a given legacy actinide, assuming that it is irradiated together with either ^{232}Th or ^{238}U, is above its equilibrium concentration in the respective irradiation chain. The equilibrium fuel composition thus provides certain information about transmutation capability. For instance, based on the example in Fig. 3 from Krepel (2021), the ^{239}Pu share in the ^{232}Th irradiation chain is very small (0.007% of the fuel) and comparable to the ^{238}Pu and ^{242}Pu concentrations. The share of other plutonium nuclides or of americium and curium nuclides is even lower. This feature makes the ^{232}Th irradiation chain attractive for utilization of synthetic actinides originated from ^{238}U irradiation. In some reactor concepts, thorium is thus proposed as a semi-inert fuel matrix (Shwageraus 2021; Wigeland, 2021). The term semi-inert refers to the fact that ^{232}Th irradiation does not extensively generate synthetic nuclides, which are typical for the ^{238}U chain. Nonetheless, it produces its own synthetic nuclides, and the benefit of this solution should be carefully evaluated, refer to Fig. 10 from Krepel (2021).

In a closed cycle, where all fed actinides are ultimately fissioned, the transmutation rate of legacy actinides is equal to their share in the feed. There are concepts, where MA act as the sole feed in a closed cycle, and their irradiation partly results in fissile Pu buildup (Artioli et al., 2007). The BR can be above one for the respective MA feed (Krepel et al., 2009). This is the reason why only the equilibrium BR related to ^{232}Th or ^{238}U should be considered for the reactors classification given in **Fig. 2**.

Transmutation generates neutron excess or shortfall, which is represented by the D-factors. As shown by the example given in **Fig. 9**, the D-factors do not differ strongly between the Th-U and U-Pu cycles. However, they vary strongly with the neutron spectrum. Transmutation of ^{242}Pu can cost around 1 neutron in a thermal spectrum while providing 0.8 neutrons excess in a fast spectrum. The dynamics of transmutation depends on the specific power of the reactor and on the absorption cross-section of the transmuted nuclide. In **Fig. 10** the absorption rate per 10^9 atoms of ^{242}Pu is shown. Obviously, the rate is higher in thermal spectra, because of the generally larger cross-section. At the same time, it is quite high also for the MFBR due to its high specific power. In general, the transmutation of legacy actinides costs less neutrons in fast neutron spectrum systems; however, it can be faster in thermal neutron spectrum.

Neutron economy

All fuel cycle performance parameters discussed above depend on the neutron economy. Nonetheless, the equilibrium multiplication factor or BG provide only one integral value for the overall neutron economy. To provide some insight, the partial neutron economy of the actinides in the ^{232}Th and ^{238}U irradiation chains is analyzed in this subchapter.

The neutron economy of the equilibrium cycle is a particular case because all nuclides creation and destruction rates are in balance, and all actinides concentrations are constant. The neutron economy, also referred to as neutron tallying, has usually two pillars. The first one is the neutron generation, which is determined by the average number of neutrons emitted per fission, labelled as $\bar{\nu}$. This number is either related to the main fissile nuclide ^{233}U or ^{239}Pu or can be a weighted average over all fissile nuclides in the core. The second pillar relies on the fact that 1 neutron is needed for sustaining the chain reaction and one for the conservation of synthetic actinides concentration. Accordingly, to start with, two neutrons must be subtracted from the balance.

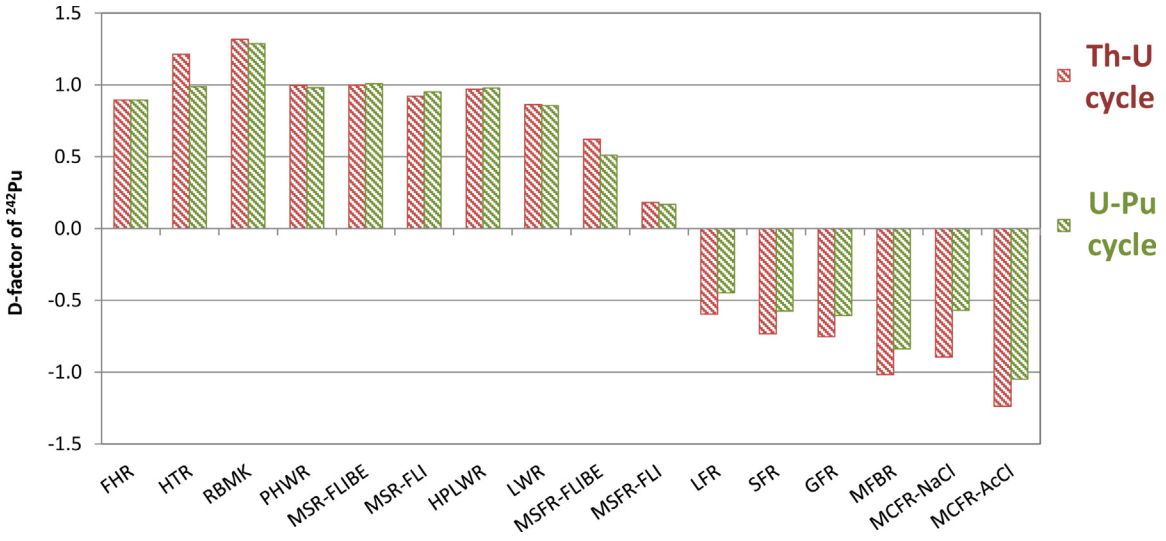

Fig. 9 D-factor of ^{242}Pu for Th-U and U-Pu cycles and 16 selected reactors.

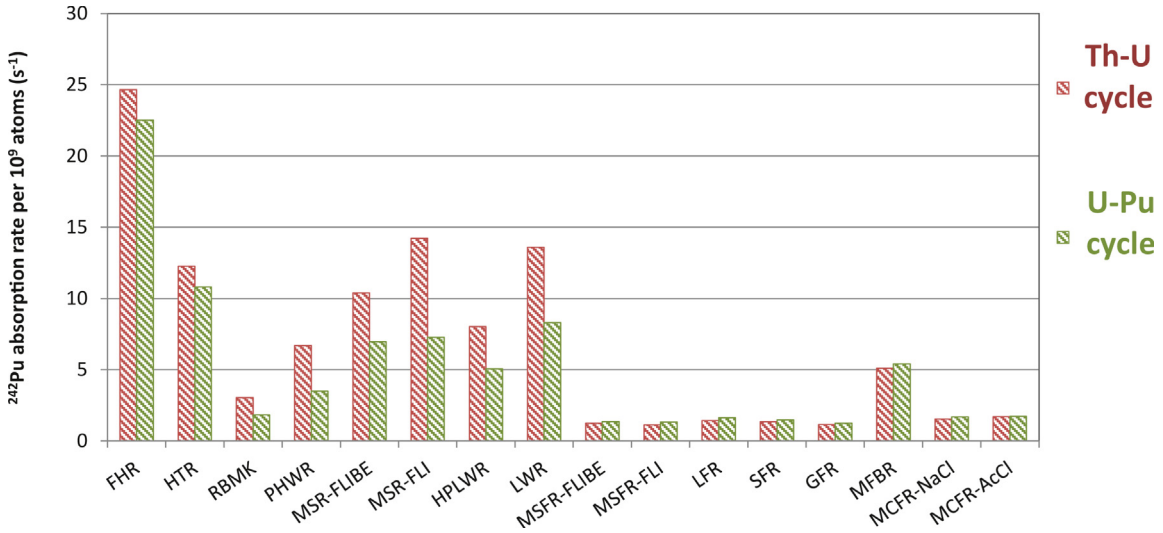

Fig. 10 Neutron absorption rate for 10^9 atoms of ^{242}Pu for Th-U and U-Pu cycles and 16 selected reactors.

η-2

The most traditional measure of the neutron economy is the η factor of the main fissile nuclide, i.e., of ^{233}U and ^{239}Pu. It is a product of $\bar{\nu}$ of the main fissile nuclide and its fission probability. The respective η-2 provides reasonable first estimate of the neutron excess. It is oriented on the conservation of the main fissile nuclide concentration. It assumes the need of two neutrons: one to be absorbed on the main fissile nuclide itself and other on the main fertile nuclide. Since η includes the fission probability it already accounts for the neutron capture by the main fissile nuclide. However, it is only approximate neutron tallying. Only main fissile and fertile nuclides and only selected reactions are considered. The impact of other nuclides and reactions in the irradiation chain is neglected. The accuracy of this estimate can be improved by:

1. Accounting for the relative share of fast Fission F_{232Th} or F_{238U} of the main fertile nuclide.
2. Accounting for the other synthetic actinides contributions to the neutron balance. This impact can be at best expressed by the D-factor of the respective ^{234}U and ^{240}Pu nuclides multiplied by the main fissile nuclide capture rate.
3. Accounting for the bypass of the main fissile nuclide by ^{233}Pa and ^{239}Np capture rate. Since this capture results in ^{234}U and ^{240}Pu buildup, this term is composed form own ^{233}Pa and ^{239}Np relative capture rate and from the ^{234}U and ^{240}Pu impact on the neutron balance.

The overall neutron balance n_{B1}, for instance for the ^{232}Th can be expressed as:

$$n_{B1} = \eta_{233U} - 2 + F_{232Th} - \frac{C_{233U}}{C_{233U} + F_{233U}} D_{234U} - \left(2\frac{C_{233Pa}}{C_{233U} + F_{233U}} + \frac{C_{233Pa}}{C_{233U} + F_{233U}} D_{234U} \right) \quad (4)$$

where F, C, and D represent the fission rate, capture rate and the D-factor. The notation for the ^{238}U irradiation chain will be similar; however, the reaction rates for corresponding nuclides ^{238}U, ^{239}Pu and ^{239}Np should be applied.

Neutrons produced per fission

A very similar method relies on the neutron balance in a self-sustaining breeder, where the average number of neutrons produced per fission is reduced by 2, assuming one neutron for fission and one for breeding. This method was actually applied in form of reactivity break-down in Krepel and Losa (2019). In this case the $\bar{\nu}$ represents weighted average over all fissile nuclides in the core. The $\bar{\nu} - 2$ provides a less precise first estimate, because it completely neglects the actinides parasitic neutron captures. The accuracy of this estimate can be increased by:

1. Accounting for the relative share of fast Fission F_{232Th} or F_{238U} of the main fertile nuclide.
2. Subtracting the Capture rate C_{Ac} of all synthetic actinides.
3. Accounting for the (n, 2n) reaction on main fertile nuclide. It should be accounted twice, because in produces an extra neutron and it reduces number of neutrons needed for main fertile transmutation.

The overall neutron balance n_{B3}, for instance for the ^{232}Th can be expressed as:

$$n_{B2} = \bar{\nu} - 2 + F_{232Th} - \frac{\sum_i C_i}{\sum_i F_i} + 2R^{(n,2n)}_{232Th} \quad (5)$$

Costs of synthetic actinides fission

Alternative neutron tallying was introduced in Krepel (2021). It relies on $\bar{\nu}$ as a weighted average over all fissile nuclides in the core, knowledge of fission rate distribution between the nuclides in the irradiation chain, and neutron cost for each nuclide creation and fission (see Table 2 in Krepel (2021)). This method is also only approximate, and more accurate values are obtained when:

1. The nucleons lost by α decay reaction are accounted for.

The (n, 2n) reaction is already included in the respective nuclides creation cost from Table 2 in Krepel (2021). The overall neutron balance n_{B3}, for instance for the ^{232}Th can be expressed as:

$$n_{B3} = \bar{\nu} - \sum_i F_i n_i - 4\sum_i \alpha_i \tag{6}$$

D-factors of ^{232}Th and ^{238}U

The D-factor of the main fertile nuclide represents the number of neutrons that are required for its ultimate transmutation. Hence, the D-factors of ^{232}Th and ^{238}U cover the neutron balance of the whole respective irradiation chains. However, the D-factors are defined as the neutron cost for ultimate transmutation. Hence, if there is a neutrons excess, the D-factors are negative. The equation for neutron balance n_{B4} has thus the trivial form:

$$n_{B4} = -D_{232Th} \tag{7}$$

Neutron economy overview

The above four neutron tallying method should provide exactly the same neutron balance. However, since not all necessary corrections are applied, the values in **Tables 1 and 2** slightly differ. Usually only the main fertile nuclide (n, 2n) reaction is accounted for. Similarly, there are several minor paths through the chain, which are not always properly considered in the neutron tallying. The values averaged over these four methods are plotted in **Fig. 11**.

The results in **Fig. 11**, even though they do not account for parasitic neutron absorption by the structural materials, coolants and moderators, illustrate the difficulty to breed in the U-Pu cycle in thermal reactors. The PHWR is the only reactor in this study, which has a slightly positive neutron balance of the actinides chain in the U-Pu cycle. Nonetheless, it is not sufficient for realistic breeding. **Fig. 11** also shows that the HPLWR, FHR, and RBMK performance in the U-Pu cycle does not differ dramatically from other thermal reactors and confirms that the very low BG in **Fig. 3** is caused by parasitic neutron captures by non-fuel materials.

The values in **Tables 1 and 2** can be also used for a general discussion about the U-Pu and Th-U closed cycles. The improved breeding in harder neutron spectra, surprisingly, is not related to the larger average number of neutrons emitted per fission. For each particular nuclide neutron economy relevant parameters are increasing with spectrum hardening. Nonetheless, the equilibrium fuel composition changes and enhances compensating effects. Thus, in the U-Pu cycle there are 2.9 neutrons emitted per fission, while in the Th-U cycle only about 2.5 neutrons. The higher number of available neutrons is the biggest advantage of the U-Pu cycle in terms of neutron economy. Another advantage of the U-Pu cycle is that up to 15% of the fissions are fast fissions of the fertile ^{238}U. Unlike the number of neutrons emitted per fission, the direct fission strongly depends on the spectrum. The strongest disadvantage of the U-Pu cycle is that the ^{239}Pu fission probability steeply decreases down to 60% with spectrum softening, whereas ^{233}U fission probability stays constant around 90%.

The dominance of the U-Pu cycle in all fast reactors ends with the MSFR, which is considered a fast reactor system. However, its spectrum has the same share of fast neutrons as the LWR (Krepel, 2021). In the Th-U cycle many thermal spectrum system have the same performance as MSFR. Unfortunately, it is the parasitic neutron capture by non-fuel materials which deteriorates the balance.

Summary

The nuclear fuel cycle relies on resources, which are not renewable and not every planet in our solar system or in the universe has them. The nuclear fission chain reaction is so far the only known alternative to nuclear fusion for producing energy from nuclear transmutation processes. The self-sustaining breeding in closed cycle is the best option to fully utilize the potential of the primordial actinides ^{232}Th and ^{238}U. The neutron economy of this process is tight, and not all advanced reactors can be operated as self-sustaining breeders. This article tried to explain the reasons for this.

Two methods have been applied for the fuel cycle performance evaluation. The first method relies on D-factors. This method was originally proposed to quantify the transmutation capability of waste burning reactors. Nonetheless, it can be applied also to ^{232}Th and ^{238}U utilization in nuclear fission reactors. The D-factors represent the number of neutrons which are needed to ultimately fission one atom of a given nuclide. Accordingly, knowledge of the equilibrium irradiation chain is needed to quantify them. The second method applied here is the equilibrium method. Similarly, like the D-factors, this method was proposed for waste

Table 1 Neutron economy of ^{238}U irradiation chain.

^{238}U chain	*FHR*	*HTR*	*RBMK*	*PHWR*	*MSR-FLIBE*	*MSR-FLI*	*HPLWR*	*LWR*	*MSFR-FLIBE*	*MSFR-FLI*	*LFR*	*SFR*	*GFR*	*MFBR*	*MCFR-NaCl*	*MCFR-AcCl*
$\bar{\nu}$ average	2.96	2.96	2.93	2.93	2.95	2.95	2.93	2.94	2.95	2.95	2.93	2.94	2.94	2.93	2.93	2.92
$\bar{\nu}_{239Pu}$	2.86	2.86	2.87	2.87	2.86	2.86	2.87	2.87	2.91	2.92	2.93	2.94	2.95	2.94	2.94	2.95
^{238}U fission prob. (F_{238U})	0.00	0.01	0.05	0.06	0.03	0.04	0.09	0.09	0.05	0.07	0.09	0.13	0.14	0.13	0.11	0.15
^{239}Pu fission prob. (F_{239Pu})	0.63	0.62	0.66	0.68	0.63	0.63	0.64	0.65	0.62	0.66	0.78	0.78	0.77	0.83	0.79	0.87
^{239}Pu capt. prob. (C_{239Pu})	0.37	0.38	0.34	0.32	0.37	0.37	0.36	0.35	0.38	0.34	0.22	0.22	0.23	0.17	0.21	0.13
^{238}U D-factor (D_{238U})	0.26	0.29	0.07	−0.04	0.21	0.18	0.04	−0.01	−0.01	−0.24	−0.62	−0.70	−0.70	−0.80	−0.69	−0.90
^{240}Pu D-factor (D_{240Pu})	0.12	0.26	0.18	0.07	0.15	0.13	0.13	0.07	−0.32	−0.60	−1.04	−1.09	−1.10	−1.27	−1.10	−1.37
Synthetic Actinides Rel. capture(C_{Ac})	1.22	1.25	1.06	0.96	1.19	1.17	1.08	1.03	1.00	0.79	0.41	0.38	0.40	0.27	0.36	0.19
Neutron balance from Eq. (4): η-2																
η-2	−0.15	−0.17	−0.07	−0.01	−0.15	−0.15	−0.13	−0.10	−0.17	−0.06	0.28	0.29	0.25	0.43	0.33	0.55
+ 1 correction term	−0.14	−0.16	−0.02	0.05	−0.13	−0.11	−0.04	−0.01	−0.12	0.01	0.37	0.42	0.39	0.56	0.43	0.70
+ 1&2 correction terms	−0.25	−0.32	−0.12	0.00	−0.24	−0.21	−0.13	−0.07	−0.03	0.20	0.60	0.66	0.66	0.79	0.67	0.90
+ 1&2&3 correction terms	**−0.26**	**−0.32**	**−0.12**	**−0.01**	**−0.24**	**−0.22**	**−0.13**	**−0.08**	**−0.03**	**0.20**	**0.60**	**0.66**	**0.66**	**0.79**	**0.67**	**0.90**
Neutron balance from Eq. (5):$\bar{\nu}$ − 2																
$\bar{\nu}$ − 2	−0.21	−0.20	0.12	0.15	−0.11	−0.08	0.08	0.09	0.26	0.44	0.70	0.77	0.78	0.82	0.75	0.93
+ 1 correction term	−0.25	−0.28	−0.08	0.04	−0.21	−0.18	−0.04	0.01	−0.01	0.23	0.62	0.69	0.69	0.80	0.68	0.90
+ 1&2 correction terms	−0.25	−0.29	−0.08	0.04	−0.22	−0.18	−0.05	0.00	−0.01	0.23	0.61	0.68	0.68	0.79	0.68	0.89
+ 1&2&3 correction terms	**−0.25**	**−0.28**	**−0.07**	**0.05**	**−0.21**	**−0.17**	**−0.03**	**0.02**	**0.00**	**0.24**	**0.63**	**0.70**	**0.70**	**0.82**	**0.69**	**0.91**
Neutron balance from Eq. (6): $\bar{\nu}$ − fission cost																
$\bar{\nu}$ − fission cost	−0.21	−0.20	0.12	0.15	−0.11	−0.08	0.08	0.09	0.26	0.44	0.70	0.77	0.78	0.82	0.75	0.93
+ 1 correction term	**−0.25**	**−0.28**	**−0.08**	**0.04**	**−0.21**	**−0.18**	**−0.04**	**0.01**	**−0.01**	**0.23**	**0.62**	**0.69**	**0.69**	**0.80**	**0.68**	**0.90**
Neutron balance from Eq. (7): D-factor																
-D_{238U}	**−0.26**	**−0.29**	**−0.07**	**0.04**	**−0.21**	**−0.18**	**−0.04**	**0.01**	**0.01**	**0.24**	**0.62**	**0.70**	**0.70**	**0.80**	**0.69**	**0.90**

Table 2 Neutron economy of ^{233}Th irradiation chain.

^{232}Th chain	*FHR*	*HTR*	*RBMK*	*PHWR*	*MSR-FLIBE*	*MSR-FLI*	*HPLWR*	*LWR*	*MSFR-FLIBE*	*MSFR-FLI*	*LFR*	*SFR*	*GFR*	*MFBR*	*MCFR-NaCl*	*MCFR-AcCl*
$\bar{\nu}$ average	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.52	2.53	2.53	2.53	2.54	2.53	2.53	2.53
$\bar{\nu}_{233U}$	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.51	2.52	2.53	2.53	2.54	2.53	2.53	2.54
^{232}Th fission prob. (F_{232Th})	0.00	0.00	0.01	0.01	0.00	0.01	0.02	0.02	0.01	0.01	0.02	0.03	0.03	0.03	0.03	0.04
^{233}U fission prob. (F_{233U})	0.90	0.90	0.90	0.90	0.89	0.89	0.89	0.89	0.87	0.87	0.89	0.89	0.89	0.90	0.90	0.91
^{233}U capt. prob. (C_{233U})	0.10	0.10	0.10	0.10	0.11	0.11	0.11	0.11	0.13	0.13	0.11	0.11	0.11	0.10	0.10	0.09
^{232}Th D-factor (D_{232Th})	−0.06	−0.14	−0.22	−0.22	−0.15	−0.12	−0.18	−0.16	−0.12	−0.20	−0.32	−0.36	−0.36	−0.35	−0.37	−0.43
^{234}U D-factor (D_{234U})	0.27	0.30	0.25	0.21	0.32	0.36	0.30	0.28	0.35	−0.02	−0.58	−0.65	−0.65	−0.80	−0.75	−0.96
Synthetic Actinides Rel. capture (C_{Ac})	0.44	0.37	0.29	0.30	0.36	0.39	0.35	0.37	0.42	0.35	0.23	0.22	0.22	0.22	0.19	0.15
Neutron balance from Eq. (4): η-2																
η-2	0.25	0.25	0.25	0.26	0.24	0.22	0.23	0.23	0.18	0.19	0.25	0.26	0.26	0.29	0.28	0.31
+ *1 correction term*	0.25	0.25	0.26	0.27	0.24	0.23	0.25	0.25	0.19	0.21	0.28	0.29	0.29	0.32	0.31	0.35
+ *1&2 correction terms*	0.22	0.22	0.24	0.25	0.21	0.19	0.21	0.22	0.14	0.21	0.34	0.36	0.36	0.40	0.38	0.44
+ *1&2&3 correction terms*	**0.06**	**0.14**	**0.22**	**0.22**	**0.15**	**0.12**	**0.17**	**0.15**	**0.11**	**0.19**	**0.32**	**0.35**	**0.35**	**0.35**	**0.37**	**0.42**
Neutron balance from Eq. (5):$\bar{\nu}$ − 2																
$\bar{\nu}$ − 2	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.52	0.53	0.53	0.53	0.54	0.53	0.53	0.53
+ *1 correction term*	0.50	0.50	0.51	0.51	0.51	0.51	0.52	0.52	0.53	0.54	0.55	0.56	0.57	0.56	0.56	0.57
+ *1&2 correction terms*	0.06	0.13	0.22	0.21	0.14	0.12	0.17	0.15	0.11	0.19	0.32	0.35	0.35	0.34	0.36	0.42
+ *1&2&3 correction terms*	**0.06**	**0.13**	**0.22**	**0.22**	**0.15**	**0.12**	**0.19**	**0.16**	**0.12**	**0.20**	**0.33**	**0.37**	**0.37**	**0.37**	**0.38**	**0.44**
Neutron balance from Eq. (6): $\bar{\nu}$ − fission cost																
$\bar{\nu}$ − fission cost	0.06	0.14	0.23	0.22	0.15	0.12	0.18	0.16	0.13	0.21	0.33	0.36	0.36	0.35	0.37	0.43
+ *1 correction term*	**0.06**	**0.13**	**0.22**	**0.22**	**0.15**	**0.12**	**0.18**	**0.15**	**0.12**	**0.19**	**0.32**	**0.35**	**0.36**	**0.35**	**0.37**	**0.43**
Neutron balance from Eq. (7): D-factor																
-D_{232Th}	**0.06**	**0.14**	**0.22**	**0.22**	**0.15**	**0.12**	**0.18**	**0.16**	**0.12**	**0.20**	**0.32**	**0.36**	**0.36**	**0.35**	**0.37**	**0.43**

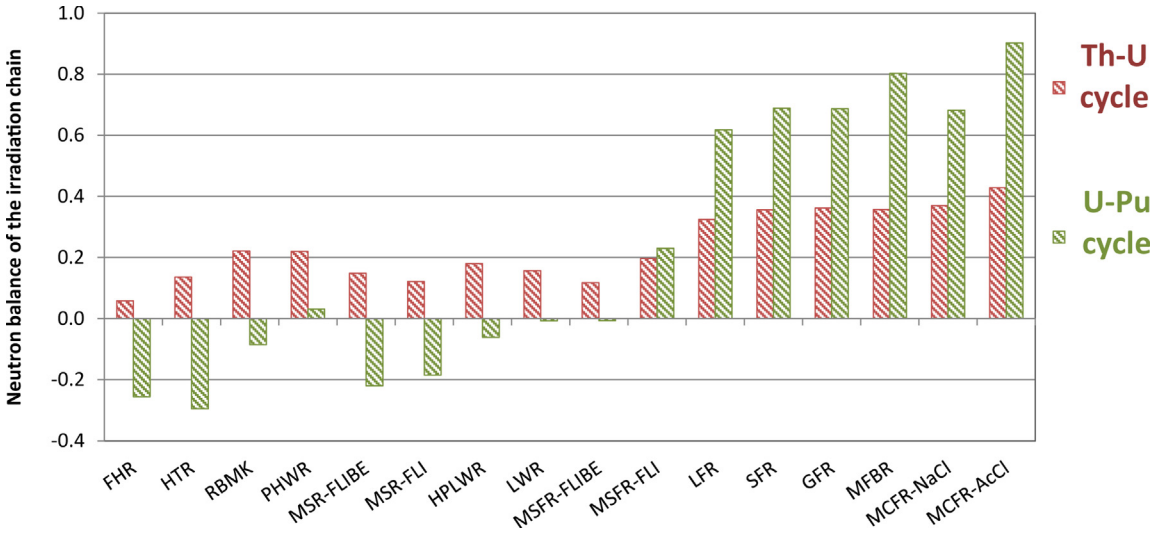

Fig. 11 Neutron balance of the ^{232}Th and ^{238}U irradiation chains. Positive numbers represent neutron excess, negative numbers neutron deficit.

burning reactors, which use synthetic actinides as a feed. However, also here if solely ^{232}Th or ^{238}U is used as a feed the resulting equilibrium represents the self-sustaining breeder. It is a characteristic of this method that the equilibrium isobreeding state is achieved also for reactors, which are subcritical in equilibrium and cannot act as a breeder in reality. The equilibrium state should be understood as an Eigen-state of the reactor and the equilibrium fuel composition as the Eigen-vector of the Bateman burnup matrix.

The knowledge of equilibrium parameters was used to assess the breeding ratio, as the foremost fuel cycle performance parameter, in each simulated reactor. The reactors can be classified into four categories based on their equilibrium breeding ratio. The second fuel cycle performance parameter, achievable burnup and its relationship with the breeding ratio, was discussed and the importance of absolute fissile fuel share was stressed. The lower achievable burnup in thermal spectrum reactors is often assigned to the higher FPs microscopic cross-sections. This is, nonetheless, only a minor contributor to the issue in comparison to the impact of the absolute fissile fuel share.

The initial fissile load for the open and closed cycle was addressed together with its relation to the achievable burnup in an open cycle. The means of criticality maintenance were not addressed as such; however possible reactivity variations in different reactors and fuel cycle types were discussed and the interconnection with breeding ratio illustrated. It is obvious that positive initial breeding gain can partly compensate for the neutron economy deterioration by FPs at the end of cycle. The transmutation capability was quantified by D-factors and by the reaction rate per atom. As expected, the transmutation of legacy synthetic actinides costs more neutrons in a thermal reactor. At the same time, the more efficient transmutation process in fast reactors can be slower.

Finally, the neutron economy of the actinides equilibrium composition, or actually of the ^{232}Th and ^{238}U irradiation chains is analyzed using four different neutron tallying methods. They all rely on the fact, that the fuel composition and reaction rates are stabilized in equilibrium. The general conclusion is that: (1) the self-sustaining breeding in closed cycle offers better neutron economy and higher achievable burnup in fast reactors; (2) the U-Pu cycle profits more from spectrum hardening and has better neutron economy, in which more neutrons are generated per fission but also parasitically captured; (3) the Th-U cycle is less sensitive to the spectrum hardening and has better neutron efficiency, in which the lower neutron generation per fission is compensated by lower parasitic captures; (4) breeding in thermal spectrum may result in prohibitively high fuel reprocessing frequency.

One potentially surprising conclusion of this study is that the better breeding in harder spectra is not related to the higher average number of neutrons emitted per fission. Even though, individual neutron yields are increasing with spectrum hardening, the changing fuel composition compensates for this effect. Hence, no matter in which reactor, in the U-Pu cycle there are roughly 2.9 neutrons emitted per fission, while in the Th-U cycle only about 2.5 neutrons are emitted per fission. The higher number of neutrons per fission, together with up to 15% of the fissions of the fertile ^{238}U that are induced by fast neutrons, is the biggest advantage of the U-Pu cycle. Unlike the number of neutrons emitted per fission, the direct fertile fuel fission probability as well as ^{239}Pu fission probability strongly depends on the spectrum. The ^{238}U fission is a threshold reaction, and the fission probability goes to zero below the threshold energy. The ^{239}Pu fission probability decreases steeply down to 60% with spectrum softening, whereas the ^{233}U fission probability stays constant around 90%. The rate of other synthetic actinides creation is thus three times higher for the U-Pu cycle in thermal reactors.

This is the third of a series of three chapters that is dedicated to the identification of the advanced reactor technologies that are capable of self-sustaining breeding when fueled with either ^{232}Th or ^{238}U and to the investigation of properties of the resulting equilibrium fuel cycles. The trivial conclusion of this study is that (1) both primordial nuclides ^{232}Th and ^{238}U can be utilized by self-sustaining breeding in closed cycle; (2) in case of ^{238}U, the B&B mode in an open cycle is also possible; (3) synthetic actinides, until

they are reasonable recoverable, should be considered as resource and catalyzer of the ^{232}Th and ^{238}U utilization; and (4) engineering and technological issues should be overcome and not allowed to discredit this natural resource.

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